Natural SUSY:

Stops, Sbottoms, Gluinos,

+ friends

Big Questions

- Is weak scale natural?
- Where is SUSY??

Whither SUSY?

Q. "Isn't it dead already?" [A. No]

Q. "Aren't all remaining models totally contrived?" [A. No]

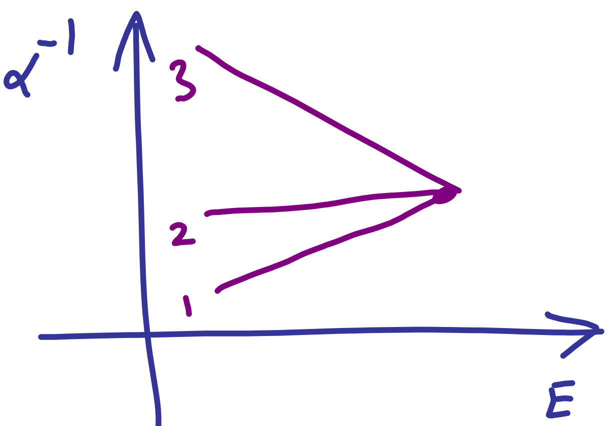
Q. "Cut the crap! Aren't you more worried about SUSY now?" [A. Not yet more worried than before LHC]

Q. "Is there anything you theorists can't weasel out of? Can anything kill low-E SUSY?"

A. Point of this talk! What must we see if SUSY naturally solves the hierarchy problem? What is a sharp measure of fine-tuning?

Much more positively: what new searches can focus on this physics and lead to first discovery?

Naturalness: #1 argument for SUSY @ L.H.C

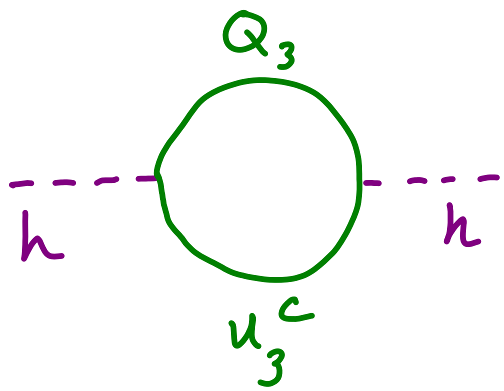


WIMP
Dark Matter

Superpartners could be @ 10 TeV (scalars anywhere)

Could be 3 TeV Wino L.S.P

Hierarchy Problem

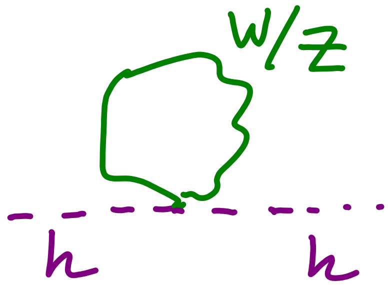


$$\delta m_h^2 \sim \frac{3\lambda_t^2}{8\pi^2}\Lambda_{UV}^2 \sim (.3\Lambda_{UV})^2$$

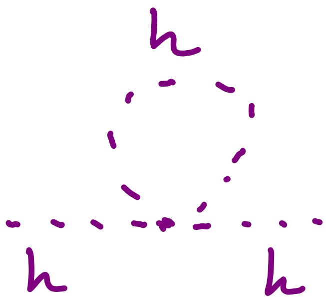
N_c

$\rightarrow$ For $m_h \sim 120$ GeV, need new colored "top partners" beneath ~ 400 GeV.

Other main quad. divergences:



should be canceled by 1.2 TeV



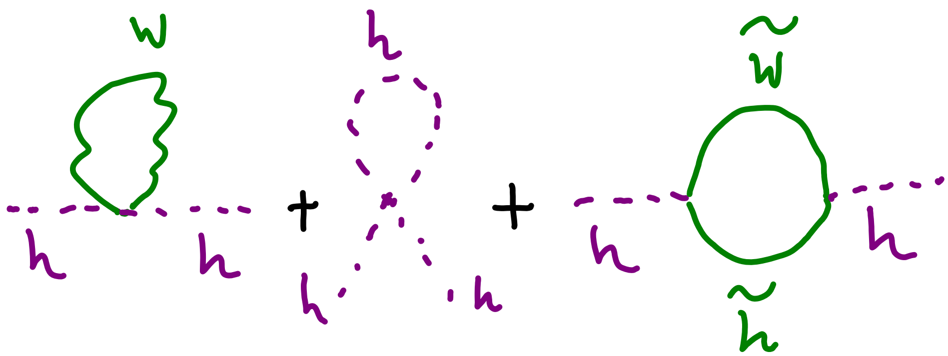
" 2 TeV

Ewk charged stuff

In SUSY:

: $\tilde{t}_L, \tilde{b}_L, \tilde{t}_R$

$\lesssim 400\,\text{GeV}$

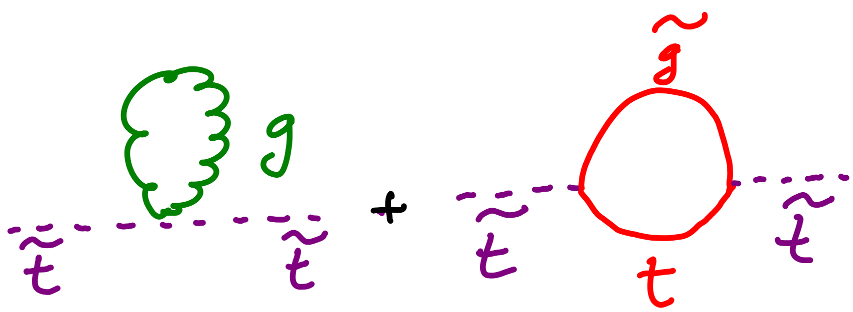


: Ewk-inos

$\lesssim 1 \rightarrow 2\,\text{TeV}$

Also need Gluino

For $m_{\tilde{t}} \lesssim 400$ GeV to be natural:



$M_{\tilde{g}} \lesssim 1.5$ TeV

Compulsory Natural SUSY

1500 ———————— $\tilde{g}$

400 ———————— $\tilde{t}_{L,R}\,,\ \tilde{b}_L$

120 ———————— h

Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2 , \left(\frac{4\, m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

[Pre-LHC SUSY Worry]

It is cumpulsory to remove these bottom-up tunings to have a natural theory. In many more complete models, extra $\log\left(\frac{\Lambda_{SUSY}}{M_{SUSY}}\right)$ factors $\longrightarrow$ need for even lighter masses.

—— $Z, W, h, \tilde{t}$

—— $\tilde{\ell}$, some ewkinos

Natural expectation

?

$\uparrow \quad \uparrow$

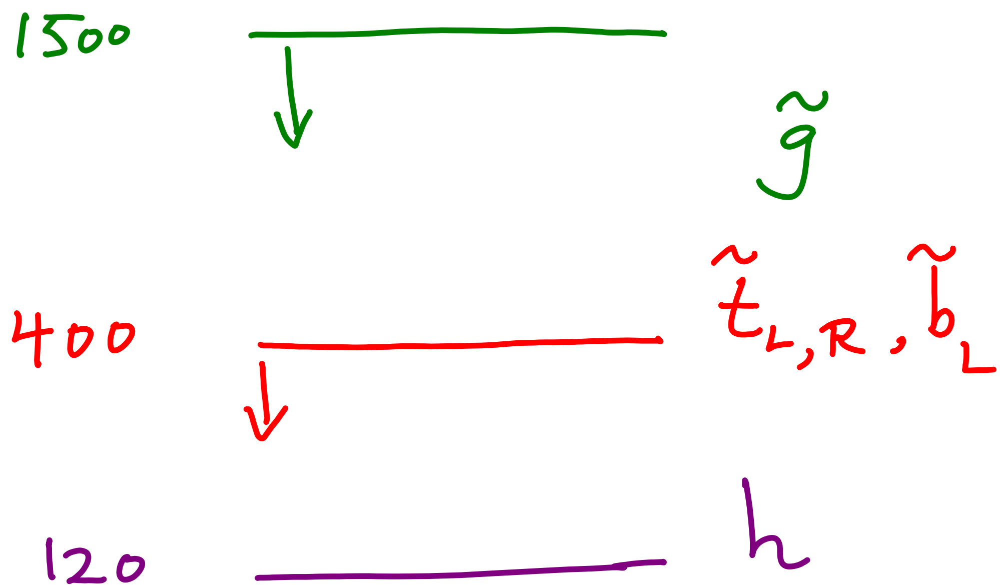
—— Z, W

Nature-al spectrum

Q. "I thought that getting higgs above the LEP bound was the big challenge to natural SUSY"

A. It's amongst our least worries. At worst – hard SUSY breaking correction to higgs quartic $(g^2 + \underset{\approx}{\delta\lambda})|h|^4$ – origin can be relegated to few-TeV scale while staying fully natural.

Compulsory Natural SUSY



Unavoidable tunings: $\left(\frac{400}{m_{\tilde t}}\right)^2, \left(\frac{4\, m_{\tilde t}}{M_{\tilde g}}\right)^2$

- This is all that is needed beneath $\sim 2\,\text{TeV}$ to soften radiative corrections to Higgs mass.
- But it is likely that other states are light for very good – albeit more model-dependent – reasons.

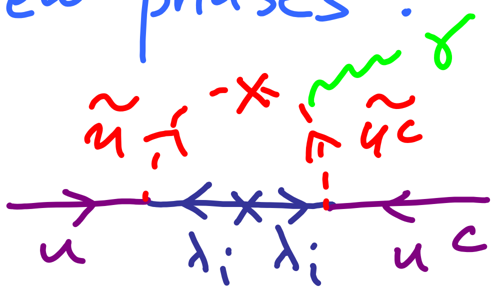
Higgsinos

- Normally $\tilde{h}_{u,d}$ mass comes from μ-term $W \supset \mu H_u H_d$ — also gives contribution to usual Higgs mass^2. Naturalness $\longrightarrow$ $\mu \sim 120$ GeV $\longrightarrow$ higgsinos $\sim$ higgs $\sim$ 120 GeV.
- [Rather baroque exception: very low-E ~~SUSY~~ theories where Higgsino mass comes from e.g. $\int d^4\theta \, \frac{X^\dagger X}{M^3} D_\alpha H_u D^\alpha H_d$, not $\int d^2\theta \, \mu H_u H_d$]

Ewk Gauginos

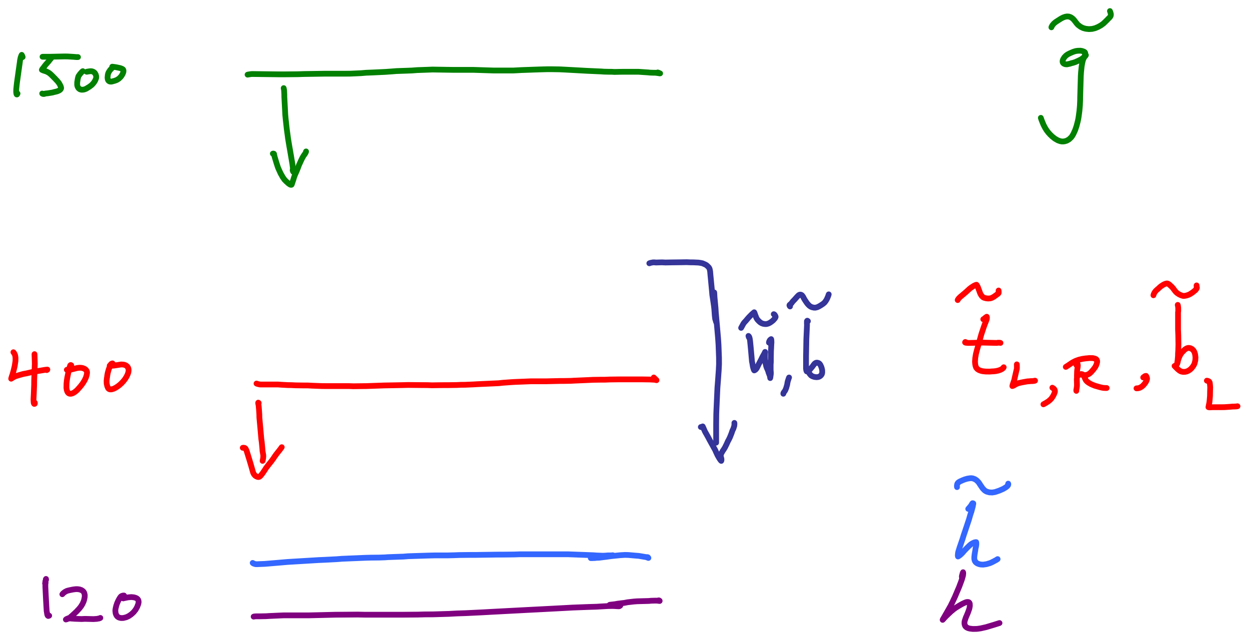
- Most of our favorite UV theories give a common source for all gaugino masses $\longrightarrow$ $\tilde{g}$ heaviest @ low-E, so $\tilde{W}, \tilde{b}$ sub-TeV.

- Common origin for gaugino masses also avoids a serious $\cancel{CP}$ problem: $(M_i^* M_j)$ are new phases:

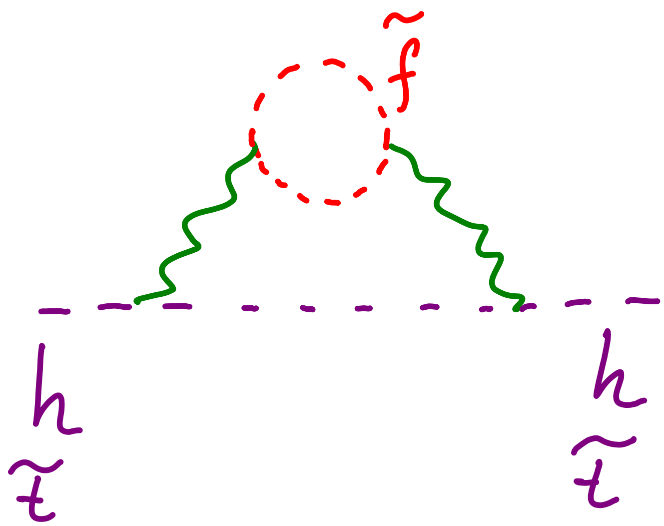


$\longrightarrow$ big neutron e.d.m, [squarks $\lesssim$ 5 TeV...]

Theorists Natural Delight



Other Sfermions



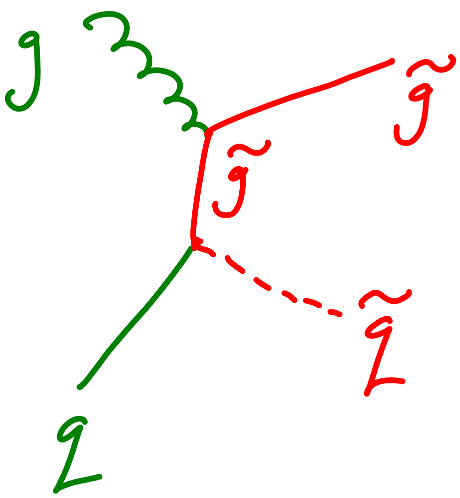
$m_{\tilde{f}} \lesssim 5\,\text{TeV} \to 30\,\text{TeV}$

running from M_{GUT} → no running

- No tuning for higgs mass
- Don't drive $m_{\tilde{t}}^2 < 0$, break color...

Q. "But don't the sfermions have to be degenerate to avoid huge FCNC's? Then you're in trouble, since the summer 2011 analyses have pushed $\tilde{g}$ + light generation squarks to 1+ TeV, so your stops must already definitely be above the naturalness bound..."

[Strongest constraints from associated squark-gluino production



which limits light gen. squarks –
as we've seen, least relevant to EWK tuning]

Safest Flavor World

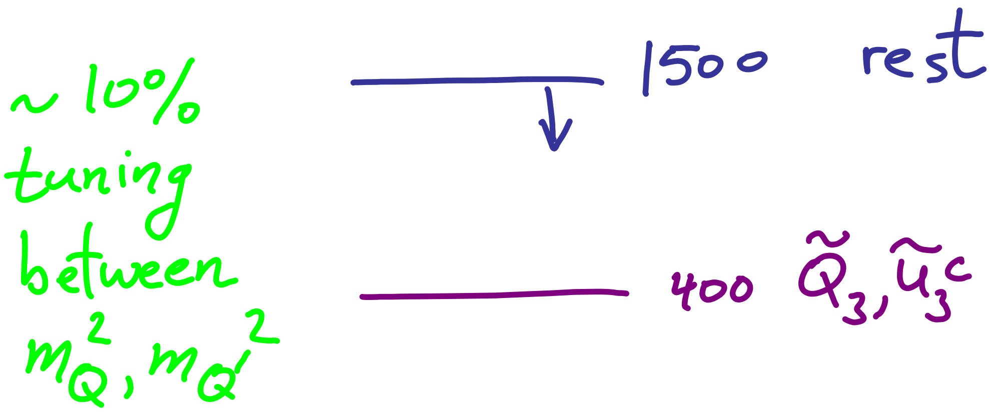
Minimal Flavor Violation: only SM Yukawas

$Y_{u,d,e}$ break $U(3)_Q \times U(3)_{U^c} \times U(3)_{D^c} \times U(3)_L \times U(3)_{E^c}$

$$\left(m_Q^2\right)_i^{\;j} = \underbrace{m_Q^2}_{\text{Universal}} \delta_i^{\;j} + m_Q'^2 \left(Y_u^\dagger Y_u\right)_i^{\;j} + \cdots$$

splits stop from first 2 gen (can e.g. result from running, ...)

So, keeping MFV, we can plausibly have



But can't parametrically separate stop without fine-tuning.

Second-Safest Flavor World

Variations on "U(2)" flavor symmetries; make first two gen. degenerate, allow any splitting with 3rd gen. Can push sfermions to ~5 TeV - solve SUSY CP problem too. [Weakens somewhat motivation for gaugino mass universality]

Maybe-safe Flavor World

The heavy ~ 10 – 30 TeV first two gen. scalars ameliorate somewhat FCNC problem, with some luck:

- Some "θ_c-ish" alignment
- ~ 10% or smaller CP phases

[Nickel + Diming the Problems away...]

Plausible Origins for 1-2/3 split

Ⓐ Light generations are composite, participate directly in strong $\cancel{\text{SUSY}}$ dynamics.

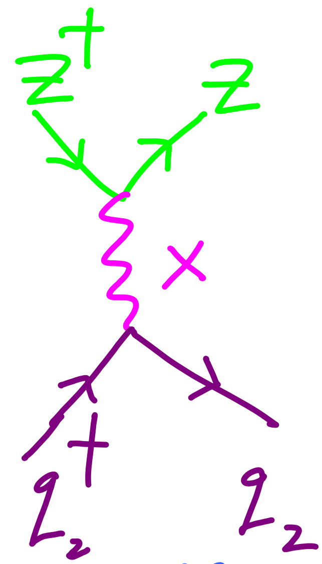
$$\underbrace{\lambda_t Q_3 U_3^c H_u}_{\text{elementary}} \qquad \lambda_c q_2 u_2^c H_u \rightarrow \frac{(\psi\psi)(\psi'\psi')H_u}{M^2}$$

big soft $\cancel{\text{susy}}$ masses $\longleftrightarrow$ Understand small Yukawas

(B) Light generations charged under a gauged flavor symmetry — which also communicates dominant S̸USY.

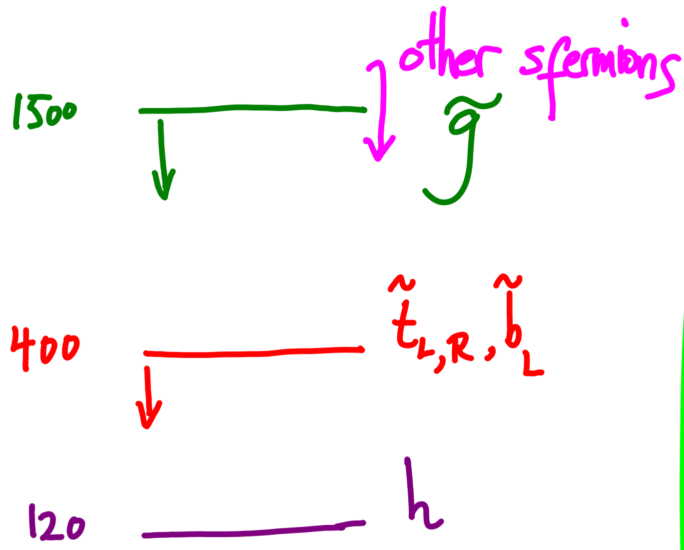
$$\underbrace{Q_3 U_3^c H_u}_{\text{neutral under } U(1)_X}$$

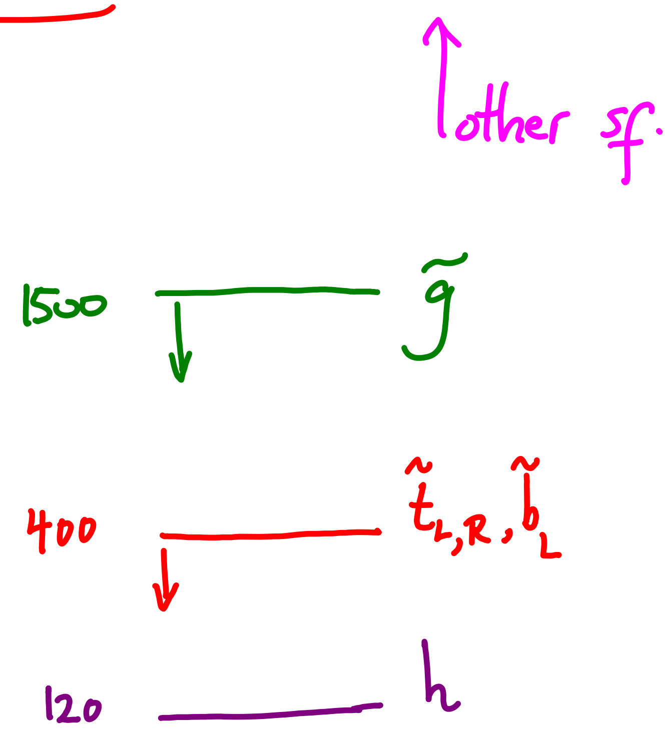
$$\underbrace{\frac{\phi_{-1}^2}{M^2} q_2^{+1} u_2^{c\,+1} H_u}_{\text{explains small Yukawa}}$$



gets big S̸USY

Bottom Line

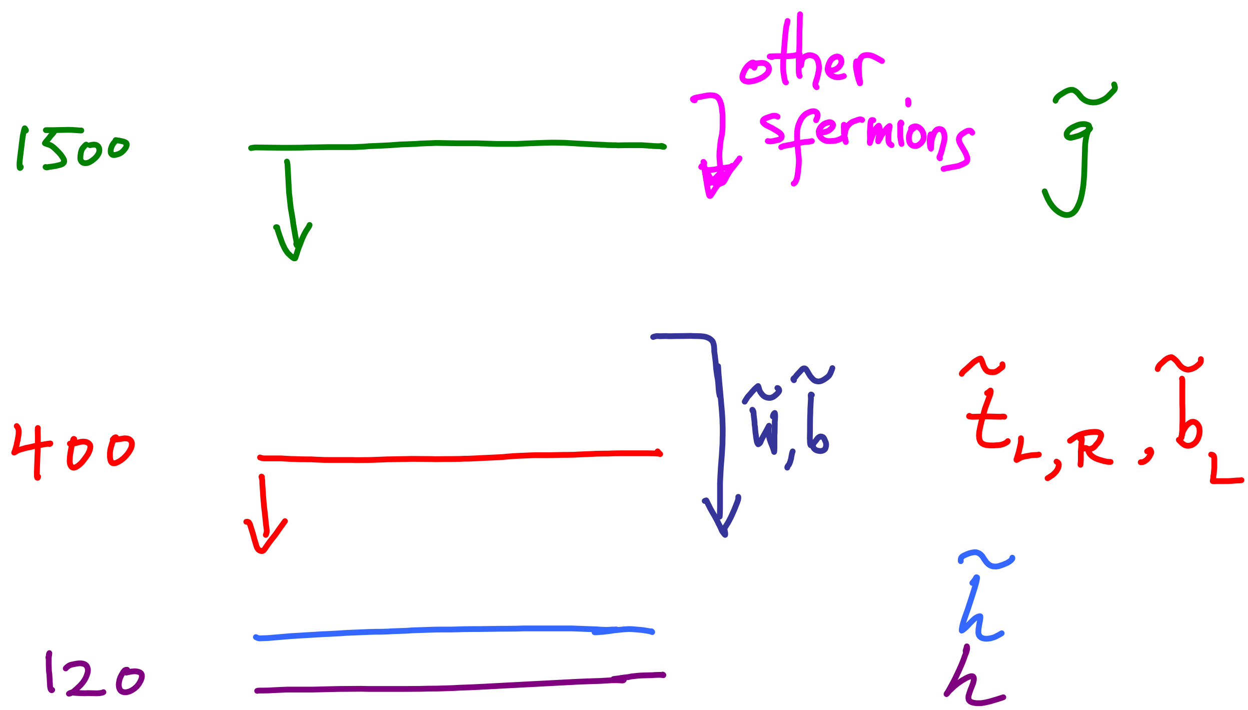




MFV: other sfermions around the corner

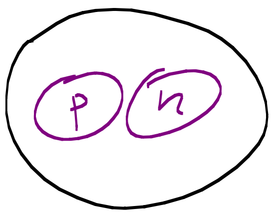
non_MFV: other sfermions won't be seen [+ UV stories likely LHC irrelevant].

Most exciting, alive + natural SUSY spectrum



Could the weak scale be tuned?

Next EFT down:



De binding energy

$\sim 2\,\mathrm{MeV}$

1 in 20 tuning

Not bound by

60 keV (!!)

few in 1000 tuning

This level tuning in SUSY – still accessible superpartners ($m_{\tilde{t}} \lesssim 3\,\mathrm{TeV}$ – eventually!)

Could it be more tuned?

Simplest Split SUSY

scalars ~ 100–1000 TeV

Higgsinos

gauginos

~ loop factor × m_s

- Tuning ~ 10^{-4}–10^{-6}
- Unification ✓
- DM ✓
- No flavor, CP, moduli, ... problems

- Here – all we have are light Ewk-inos + gluino.

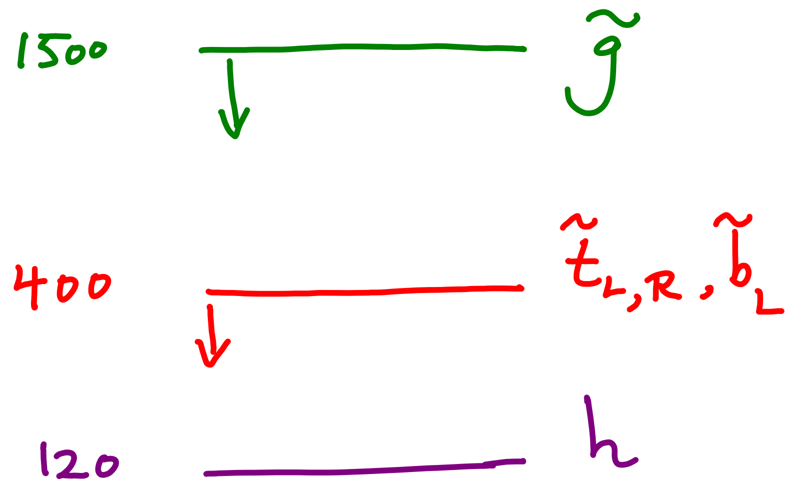
Great to see

Long lifetime possible smoking gun

(stopped gluinos, displaced vertices...

less lucky – gluinonium, ...)

SUSY Bull's Eye



No wiggle room. Limits: sharply quantify tuning.

DISCOVERY $\longrightarrow$ EUPHORIA!